51. IWK

Internationales Wissenschaftliches Kolloquium
International Scientific Colloquium

PROCEEDINGS

11-15 September 2006

FACULTY OF ELECTRICAL ENGINEERING AND INFORMATION SCIENCE

INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING - DEVICES AND SYSTEMS, MATERIALS AND TECHNOLOGIES FOR THE FUTURE

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

TECHNISCHE UNIVERSITÄT
ILMENAU

Impressum

Herausgeber: Der Rektor der Technischen Universität Ilmenau
Univ.-Prof. Dr. rer. nat. habil. Peter Scharff

Redaktion: Referat Marketing und Studentische Angelegenheiten
Andrea Schneider

Fakultät für Elektrotechnik und Informationstechnik
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Redaktionsschluss: 07. Juli 2006

Technische Realisierung (CD-Rom-Ausgabe):
Institut für Medientechnik an der TU Ilmenau
Dipl.-Ing. Christian Weigel
Dipl.-Ing. Marco Albrecht
Dipl.-Ing. Helge Drumm

Technische Realisierung (Online-Ausgabe):
Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Verlag: isle
Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilrnenau

ISBN (Druckausgabe): 3-938843-15-2
ISBN (CD-Rom-Ausgabe): 3-938843-16-0

Startseite / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=12391

51st Internationales Wissenschaftliches Kolloquium
Technische Universität Ilmenau
September 11 – 15, 2006

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Permanent Magnet Low-Speed Synchronous Generator for Wind Applications

1. Introduction

Wind power industry and technology have been developed very fast around the world during last 10…15 years. Mostly powerful grid-connected megawatt scale wind generators 0.6…4.5 MW per unit are progressively manufactured and installed as pollution free sources of renewable energy last years. A record installation of more than 6000 MW new wind power generators in 2005 has been achieved in EU countries [1].

At the same time many smaller wind turbines are required for certain installations and local consumption as maintenance-free independent power supply. A small-scale wind power turbine of 0.2…30 kW capacity may be used as a flexible and vital alternative for individual or property power demand in insolated regions or locations. Some studies in the field of small-scale permanent magnet (PM) excitated synchronous generators have been directed to the wind power applications [2, 3, 4].

In this paper the results of study of low-speed directly-driven permanent magnet excitated synchronous generators by rated power of 5…10 kW for small-scale wind power applications have been presented.

2. Primary Magnet Field of PM Generators

The primary magnetic field caused by PM poles have been modelled as well as analysed by the method of conformal mapping. The PM poles may be designed with or without ferromagnetic pole shoes. In this paper the distribution of magnetic field caused by PM poles without ferromagnetic shoes has been studied.

A linear model of the PM synchronous generator for analysis of magnetic flux distribution in the non-magnetic gap between armature and inductor ferromagnetic cores has been created (Fig.1). By this model the distribution of magnetic flux caused by permanent magnets to main flux Φ_{01} and leakage flux Φ_{s} has been described. The influence of armature slots will be taken into consideration by Carter factor.

For analytical analysis of primary magnetic field distribution in the air-gap a model for the non-magnetic gap including the zones of both air-gap and permanent magnets between the armature and inductor ferromagnetic surfaces was created. Instead of permanent magnets a system of linear surface current densities $\pm\sigma_s$ have been included into the model (Fig. 2).

For the zone A-B-C-D of the model the distribution of magnetic field caused by surface current densities $\pm\sigma_s$ may be solved by Maxwell equations, but it will be complicated to use this solution for practical calculations.

In this study the method of conformal mapping has been used for analysis of the magnetic field distribution. A model for one half of a PM pole zone for the plane $z = x + jy$ has been created (Fig. 3, a). As the result of conformal mapping this model will be performed to a new model for the plane $w = u + jv$ (Fig. 3, b).

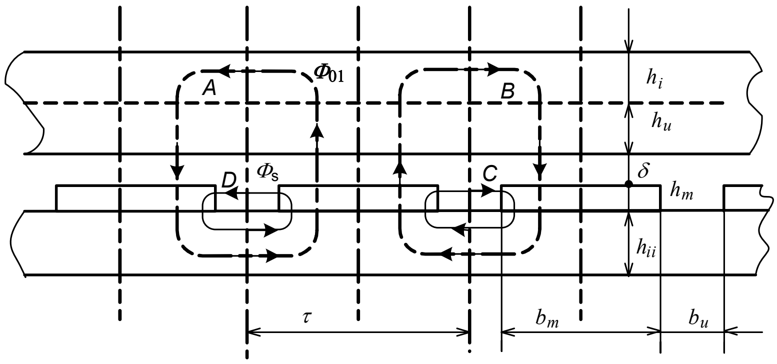

Fig. 1. A linear model of the air-gap zone for a PM synchronous generator.

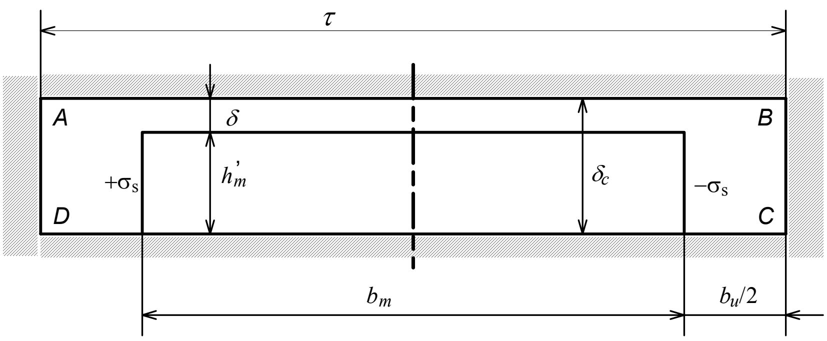

Fig. 2. A model of an equivalent non-magnetic gap of PM generator.

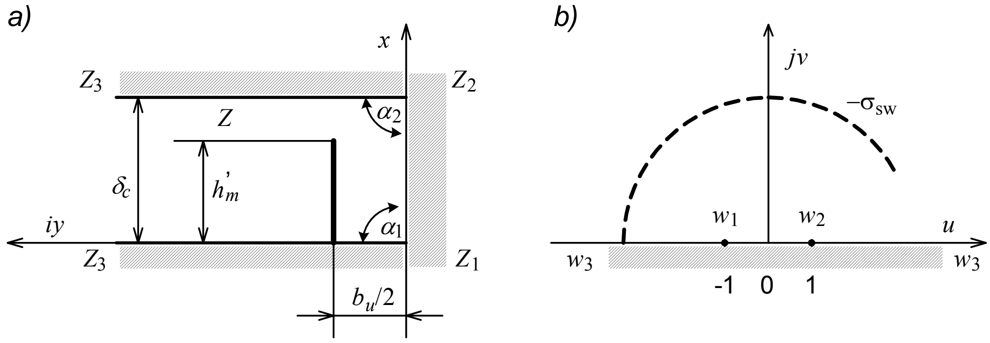

Fig. 3. Conformal mapping of the model for air-gap of PM generator.

By the means of conformal mapping method for this model the distribution of primary magnetic flux density in air-gap at first for the w-plane B_w and then it was transformed to the real z-plane B_z as determined:

$$B_z = B_a \sqrt{\left|u^2 - 1\right|} \frac{1}{n} \sum_{i=1}^{n} \frac{(u - u_{si})}{(u - u_{si})^2 + v_{si}^2},$$

where the calculated value of magnetic flux density in air-gap on the axis of permanent magnets

$$B_a = \mu_0 \frac{I}{\delta_c} = \mu_0 \frac{F_c}{\delta_c}$$

and the calculated magnetomotive force of permanent magnets

$$F_c = H_c \cdot h_m.$$

The distribution of relative magnetic flux density in air-gap on the stator core surface calculated by these equations was compared by the experimental data (Fig. 4). There was a good correlation between calculated and experimental data.

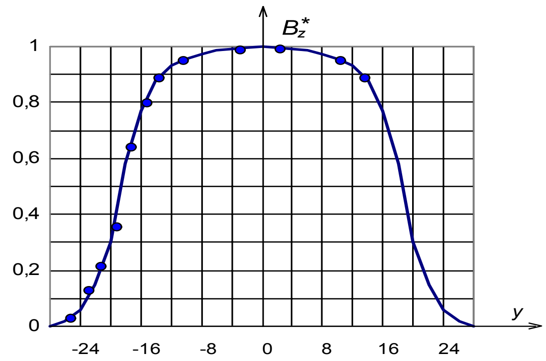

Fig. 4. The calculated and experimental distribution of relative magnetic flux density in air-gap on the surface of armature core.

As a result of this analysis the main magnetic flux distribution in air-gap and magnetic cores of both armature and inductor will be calculated. The distribution of leakage flux will be taken into consideration.

For simplified analysis of both main and leakage fluxes the method of equivalent lumped parameter magnet circuit in accordance with the topology of the PM machine may be used (Fig. 5).

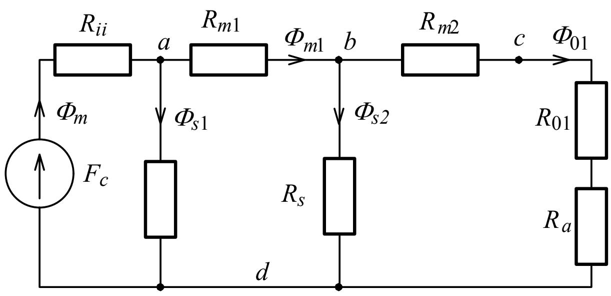

Fig. 5. A lumped parameter magnetic circuit for PM synchronous generator.

To get the more exact distribution of magnetic fluxes from the permanent magnets in the air-gap of the machine, the surface of magnets has been devided into two parts causing two paths of leakage fluxes Φ_{s1} and Φ_{s2} respectively. Using this method the main magnetic flux Φ_{01} as well as the distribution of primary magnetic field was calculated for comparision.

For design of PM machine the influence of air-gap of varying thickness between PM poles and stator core surfaces have been analysed to determine the way to transform it to an equivalent airgap of constant thickness. As a result some corrections have been used for design calculations of PM synchronous generators.

3. Magnetic Field in Axial End Part of PM Machine

The distribution of both primary and secondary magnetic fields in the zone of axial end part of air-gap in PM machines is vary complicated. The relatively large non-magnetic gap between armature and inductor cores is the main reason to cause a considerably different influence of end effects to the distribution of primary and secondary magnetic fields.

A model of the end zone of air-gap and end surfaces of stator and rotor cores was analysed using the method of conformal mapping. The influence of end surface of permanent magnets was taken into consideration using equivalent surface current densities. The results were compared with the distribution of end-zone magnetic field modelled by finite element method. There is a good correlation between the results of these different methods. By the classical theory of synchronous machines the equivalent axial length of the air gap L_{eq} may be calculated as next:

$$L_{eq} = L_m + \delta \cdot \beta,$$

where L_m – actual length of air-gap,

δ – thickness of air-gap,

β – coefficient to take into account the influence of end zones of air-gap.

As a result of this study, it may be recommended for design and calculation of primary magnetic field of PM generators, the equivalent length of the air-gap may be taken the same as the geometrical length ($\beta_p = 0$).

By the results of conformal mapping for the secondary magnetic field of armature reaction the coefficient for equivalent length of air-gap β_s for the studied model may be taken as $\beta_s = 1.5 \ldots 2.5$. For the designed in this study different constructions of PM generators 5…10 kVA the length-increasing factor was calculated as $\beta_s = 2.02 \ldots 2.10$. For classical synchronous machines with field winding exitation this factor is taken as $\beta_s = 2$.

4. Armature Reaction in PM Generators

Under the load conditions the currents in armature winding of PM generator will cause the secondary magnetic field, which will cause the armature reaction affecting to the resulting magnetic field. The *d*- and *q*-axis components of armature reaction have been studied.

As a result of the *q*-axis component of armature reaction a distortion of the magnetic field in the teeth and yoke zone of armature first of all will be caused. The *q*-axis magnetic flux component linking with the inductor and permanent magnets is relatively small. The *d*-axis component of armature reaction will cause the reduction of magnetic flux density about 12…15% in teeth zone of armature core by rated load currents. As the results of both *q*- and *d*-axis components of armature reaction there will be reduction of magnetic flux in teeth zone 17%. In this reduction the influence of slot leakage flux has been taken into account.

Due to very low permeability μs for permanent magnet material the equivalent thickness of non-magnetic gap between armature and inductor magnetic cores is relatively large. The influence of a large non-magnetic gap will reduce the affect of armature reaction in PM machines compared to conventional synchronous machines [5].

5. Design and Experimental Study of PM Generator

A prototype of 10 kW PM synchronous generator having fractional two-layer armature winding was designed using analytical methods and results of conformal mapping studies. For comparison the distribution of magnetic fields by finite element method using the program Maxwell was analyzed.

For the prototype PM machine there was chosen the number of armature slots 60 and the number of pole pairs 14. Rectangular NdFeB magnets were fixed in the nests on the radial surface of inductor magnetic core. The length and outer diameter of air-gap are 240 mm and 242 mm respectively. The line voltage by open-circuit conditions of 488 V and by nominal load of 400 V and 50 Hz frequency for the nominal rotational speed of inductor 214.3 rpm was prognosticated by design calculations.

An experimental study and verification of designed and predicted no-load and load characteristics and behavior of the PM generator prototype has been made. The characteristics by three-phase resistive load and by a diode rectifier with resistive load were studied and compared. In experimental studies the line voltage by open-circuit and nominal load and nominal rotational speed conditions was measured as 493 V and 405 V respectively. The waveform of line voltage by open-circuit or symmetrical three-phase resistive load was almost sinusoidal, but phase voltage has significant influence of the 3-rd harmonic affects.

6. Conclusions

A 10 kW low-speed PM synchronous generator for wind power applications was designed and experimentally tested. A fractional two-layer armature winding to minimize the influence of ripple torque was used. The NdFeB rectangular magnets were fixed into the nests on the surface of the inductor yoke. The analytical study of primary magnetic field distribution by conformal mapping and finite element methods was compared with experimental data from PM model and prototype machine tests. There was a relatively good correlation between the analytical and experimental data.

As a result of tests a very low level of ripple torque as well as line voltage of almost sinusoidal waveform and predicted level was achieved. There was noticed the tendency, the calculated line voltages for no-load and different load conditions were lower compared to experimentally measured voltages by 0.5…1.3%. It was caused mainly by the relatively lower experimental temperatures of magnets compared to calculated temperatures by design. Development of more accurate thermal analysis methods for PM machine will make it possible to achieve a more accurate level of electromagnetic analysis on the PM synchronous generators for wind power applications.

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